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Extended summary

Design of a comfort-based smart metering system for sport and recreational buildings

Curriculum: Ingegneria Meccanica e Gestionale

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Abstract.

This work summarizes the design and development of a comfort-based smart metering-system dedicated to Sport Facilities. Smart metering systems are usually designed only to monitor energy, while comfort is often neglected. This is on the contrary particularly important because of the intense activities carried out and the desire to maintain a sense of well-being. The whole functionalities are showed in agreement with this approach, that concerns the energy monitoring, the comfort evaluation, the sensors network optimization, data analysis and display for the end user. Comfort indices (PMV, predicted mean vote, and PPD, predicted percentage of dissatisfied) are used instead of the only air temperature, accompanied by a calibration procedure and global sensitivity analysis. The calibration procedure is based on the comparison between subjective comfort through surveys and objective measurement with a microclimate station. This analysis, applied at two real cases (swimming pool and gym), reveals a drift of the thermal neutrality which is used as correction factor. The global sensitivity analysis is useful on one hand to apply some simplifications hypothesis to avoid the measurement of the low-sensitive variables and, on the other hand, to identify which variables are more important in this field of application. The measurement system has to be deployed in very large spaces with a sufficiently cost-effective sensor network and with an accuracy suitable for feedback to the control systems. In order to reduce the impact of the uncertainty, due to the horizontal distribution and air stratification, a dedicated tool has been developed which provides the optimal number and position of temperature sensors in the space with a potential energy saving that has been evaluated with a simulation model. The designed solution is part of the development of a dedicated BMS (Building Management System) for sport and recreational buildings in the framework of the European Project FP7 SportE^2.

Keywords. Smart metering, Sport buildings, Thermal comfort, Optimization.

1 Problem statement and objectives

The European Sport and Recreation Building Stock accounts for about 1,5 Million buildings in Europe. They represent about the 8 % of the overall building stock while the overall energy consumption is around 10 % of the sector. Sport facilities share some characteristics with offices and other commercial buildings, but are unique by their nature, their energy consumption profiles, the usage patterns of people inside, ownership and comfort requirements. In this context the presented thesis deals in particular with the design of a monitoring strategy (what to measure, how and where), which is at the base of the Smart Metering module under development within the European Project SportE². Many solutions have been previously developed to analyze energy performances in different ways [1][2], at different levels of accuracy and each tool quantifies the building energy behavior to fit user's needs [3][4], but no holistic approach specific for monitoring sport buildings can be found in the state of the art, that is the starting point of this analysis. The basic idea of the present approach is very simple: the environment of sport facilities should be managed and controlled not only to save energy and costs, but also to maximize people comfort in all the different functional areas. Thus, the idea is that a smart monitoring systems should be able not only to provide detailed information on energy use and generation, but also on the perceived comfort level in the different areas. The knowledge of such real-time data could give to the facility manager the possibility to take decisions on control strategies not only necessarily based on energy savings: for example, he could decide to improve the comfort when the facility is crowded with customers, even if this will cost a bit more. In addition, these information can also be used to feedback automatic control and optimization strategies. In order to practically use thermal comfort as a performance indicator, in many recent applications PMV/PPD-based (PMV: Predicted Mean Vote, PPD: Predicted Percentage of Dissatisfied) control systems have been developed and demonstrated for residential and office buildings (e.g. [5][6][7]). It has also been shown that a PMV-based control system has interesting potentials for energy savings with respect to thermostatic control, for example for cooling in glass façade buildings [8]. For this peculiar class of commercial buildings only very recently comfort is considered in some specific applications, e.g. for heat pump control in a swimming pool [9] or in CFD (Computational Fluid Dynamics) simulations in the design phase [10]. However a methodological approach is still missing and needed. Thus parameters to be monitored in different sport and recreation facilities are evaluated and defined in this document. In order to implement this smart monitoring approach, also the metrological problem of accurately measuring PMV comfort parameters in sport facilities has to be addressed. [11] deals with the minimum characteristics required for instruments to be used for the measurement of physical parameters. Sensor networks for PMV measurements have been developed [12][13], but the application for sport facilities is not straightforward mainly for two reasons: i) PMV and PPD parameters are basically defined for normal living environment, so they have to be differently defined and calibrated for people doing sport activities; ii) measurements have to be performed in very large spaces (court, gyms, swimming pools, etc.) with relevant air stratification, with a sufficiently cost-effective sensor network and with an accuracy suitable for feedback to the control systems. The first reason is also stressed by the fact that thermal comfort is based on a model which considered the occupants as *passive subjects of thermal exchange*. In the last years several studies [14][15] call this model in question because it does not take into account some crucial factors as the climate, context of activity or the thermal history of the subject. Thus the concept of *adaptive* has been introduced in this work. This adaptive approach illustrates how the thermal history of each subject can modify his thermal preference. Obviously, this is more essential for the sport building where the context of activity is one of the most important factor. In order to evaluate the impact of the subjectivity a dedicated study in two typical sport areas has been performed with subjective (surveys) and objective (microclimate station) measurement of the comfort indices. The analysis of this test shows how the neutrality point of comfort can drift in function of the subjective factors. Thus the application of thermal indices to sport facilities needs of a more accurate calibration considering the type of activity, the season and the thermal history of the subject. The proposed methodology requires the right level of accuracy for the measured variables and, when applied to sport areas, the main uncertainty is related to the measurement of the air temperature in large spaces. Furthermore there is lack in the literature on how to improve the accuracy of the measures of temperature and humidity in these type of areas. This has a double impact on the building management, in fact it is used for the HVAC control and for the evaluation of the thermal comfort in the space. Here the reason for the development of a software tool cable of optimizing the sensors position in large spaces presented in this thesis. The tool, starting from user data input of the building, builds a sub-zonal thermal model of the area (e.g. the swimming pool) and create a virtual sensors network. Each subzone has a temperature sensor. Then a multi-objective genetic algorithm find the number and position of the sensors that minimize the RMSE (root mean square error) between the temperature measured by the solution with all sensors installed in each subzone and the solution found by the algorithm.

2 Research planning and activities

The proposed system is conceived to provide high level information to four main actors:

1. The facility manager trough dedicated user interface and tools with which he has the clear picture of how energy is used within different areas in the building and the respective comfort level. Thus, he can decide how to manage the facility and how much he is spending to provide well-being and comfort to his users;
2. Users through the display dashboard that makes them aware of the facility management concerning the use of energy and comfort;
3. The BMS control system, to enable needed data for better control;
4. The BMS management system, to produce optimal decision taking based on the processed data collected by the metering system.

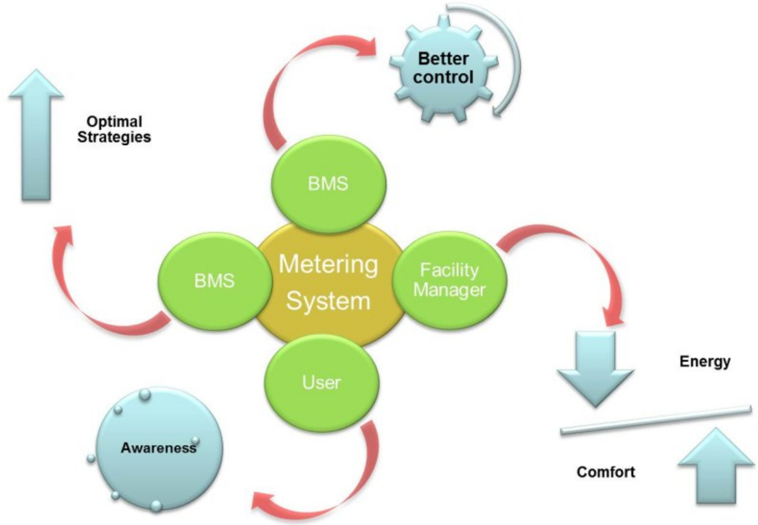

Figure 1 Concept of the proposed smart metering system

The required objectives are reached by a set of functionalities (hardware and software) which is shown in Table 1 and defines the needed research path for designing.

Table 1 System functionalities

Functionality	**Progress beyond SOA**	**Scientific approach**
Knowledge of real-time energy consumption via sub-metering and proper visualization/analysis and grid exchange	Integration of multivendor products/systems	Sensors network installation and construction of a baseline for assessment (energy audit used as reference for project assessment)
Knowledge of area's comfort condition using PMV	Real time comfort indicators never used in sport facilities	Definition of methodology for PMV measurement in sport facilities
Optimization of temperature and humidity measurement in large spaces (e.g. swimming pool)	No existing approach in the SOA	Genetic algorithm that finds the best sensors number/position using a thermodynamic identification function

The development of these functionalities requires the following activities:

- Definition of performance metrics (primary for the whole building and secondary for areas and subsystems);
- Definition of the measurement methodology (what, where and how to measure);
- Design of the hardware architecture on which the approach relies;
- Calibration procedure for the application of a comfort theory to sport areas, this step is supported by a global sensitivity analysis and a comparison between subjective and objective (measurement) approach;

- Development of a hygro-thermal modeling approach capable of reproducing the thermal air distribution in the spatial domain;
- Development of a multi-objective genetic algorithm to find the optimal sensor placement;
- Integration of modeling and optimization tools in a unique software with a user interface for data input and output.

3 Analysis and discussion of main results

A complete guideline for the choice of measurement technology, point and method is presented. The guide is completed by the required data analysis to obtain the performance indicators. An example of the content of this guide is reported in Figure 2 concerning a swimming pool. In order to assess feasibility of the proposed monitoring approach, typical data of a swimming pool have been simulated. The aim here is to highlight the information achievable for the smart monitoring system and example of following decision taking procedures.

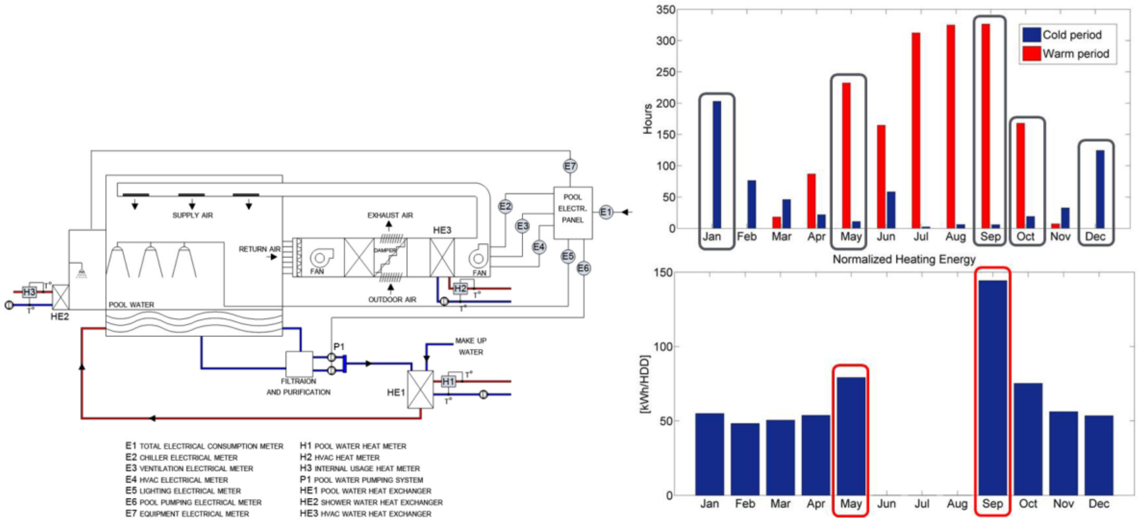

Figure 2 Monitoring solution for a swimming pool and related data analysis to identify overheating and underheating periods

Thus the use of these comfort indicators can open new strategies for a better control of the building. In fact a clear example can be shown if we compare the comfort figures with the energy figures related to the same period of time. As highlighted in Figure 2 the comfort indicator can identify the over/under heating period and can be used to find the optimal balance between consumption and comfort in the monitored area.

The proposed methodology relies on the comfort measurement. The selected method to evaluate comfort level is the ISO-PMV which constitutes an application of the Fanger's theory. The possibility of applying this methodology at sport environments is analyzed with a global sensitivity analysis (uncertainty and sensitivity).

Table 2 Summary of the statistical characteristics of the PMV distribution obtained from the uncertainty analysis performed using Monte Carlo analysis to investigate the uncertainty of the PMV relation due to the input variables measurement

	Global	**Pool**	**Gym**
Mean	0.60	0.97	1.11
Variance	5.47	1.00	2.59
Standard deviation	2.34	1.00	1.61
Minimum	-22.07	-5.00	-11.50
Maximum	5.50	3.05	4.57
Range	27.56	8.05	16.08

Table 2 shows the outcomes of the uncertainty analysis where the three distributions can be considered normally distributed. Thus the total uncertainty of the comfort model is expressed by the mean, variance and standard deviation. Each case shows a mean value major then 0, that indicates a tendency of the model to over-estimate the PMV as stated also by [16]. One of the main reason of the bias can be attributed to the metabolic level, in fact the higher mean value occurs in the case of a gym where the range of metabolic rates is wider while for the pool environment this factor is balanced by the low level of clothing.

The Pearson coefficient is evaluated in order to assess the influence of each variable input [17] and the result is summarized in Table 3.

Table 3 Correlation coefficients between the PMV and the variable inputs (air temperature t_a, mean radiant temperature t_r, relative humidity *RH*, air velocity v_a, metabolic rate *M* and clothing level *CLO*)

Correlation Coefficient	t_a	t_r	***RH***	v_a	***M***	***CLO***
PMV Global	0.39	0.28	0.05	-0.12	0.58	0.43
PMV Pool	0.46	0.49	0.13	-0.13	0.61	0.17
PMV Gym	0.32	0.25	0.08	-0.01	0.72	0.39

In the general application the most significant variables are the ambient air temperature, the metabolic activity and the clothing factor. This fact underlines the weight of subjective factors in the comfort model. When applied to well defined environments the variability of the variables is restricted causing a lower standard deviation and a change of the most influencing variables. In fact in the swimming pool the PMV results more sensitive to the measurement of the temperatures (both ambient air and mean radiant). Moreover the metabolic rate remains the most sensitive factor which needs of more accurate estimation as described in [18], especially for people with higher activities.

Results of the global sensitivity analysis are confirmed by two measurement campaigns where subjective and objective comfort measurement were done. The data analysis applied can identify the real comfort sensation providing the thermal neutrality given by the subjective factors as shown in Figure 3.

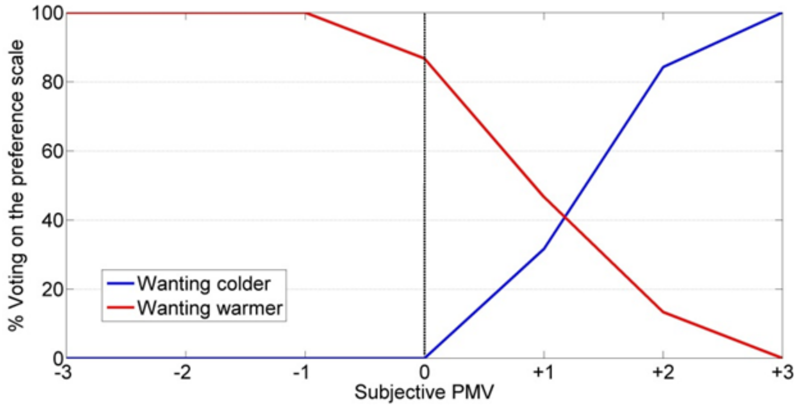

Figure 3 Result of the subjective comfort analysis for a swimming pool. The real thermal neutrality point, given by the intersection between wanting colder and warmer curves, drifts towards positive values of PMV

First application for the described procedure is performed for swimming pool and gym/fitness environments. The calculation of PMV, PPD and long term index is converted in an algorithm, integrated in the smart metering system, and corrected with the thermal neutrality drift obtained with the explained analysis.

The main source of uncertainty when measuring comfort to be used for optimal control is related to the measurement of environmental thermal conditions, especially in sport facilities where large spaces occur. To overcome this issue a stand-alone software, called Sensors Optimization Unit (SOU), is developed and it is composed of three different components: Graphical user interface, thermal modeling and optimization tool. In details the main container is a window form application developed in VB.NET which manages data flow between the components as explained in Figure 4.

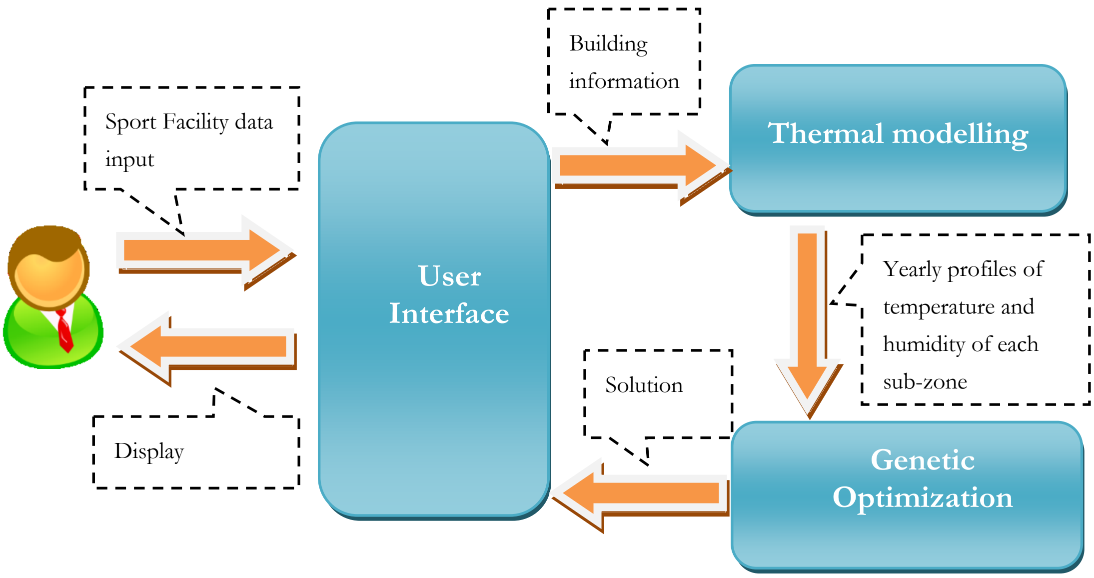

Figure 4 Optimization software dataflow

The hygro-thermal identification of the environment is done with a sub-zonal modeling approach which determines yearly temperature and humidity profiles of the sub-zones in the space. In this case a six sub-zones model is built. Then the genetic algorithm finds solutions minimizing the Root mean square error respect to the ideal solution where a sensor is installed in each sub-zone and the number of sensors used. Measured data, from the real case study where the software has been tested, are used for an initial validation of the prototype. In practice the real temperature and humidity data collected from field monitoring are submitted to the optimization tool that is implemented in the SOU. The output consists of two solutions (one and two sensors) which are the real optimal sensors positioning.

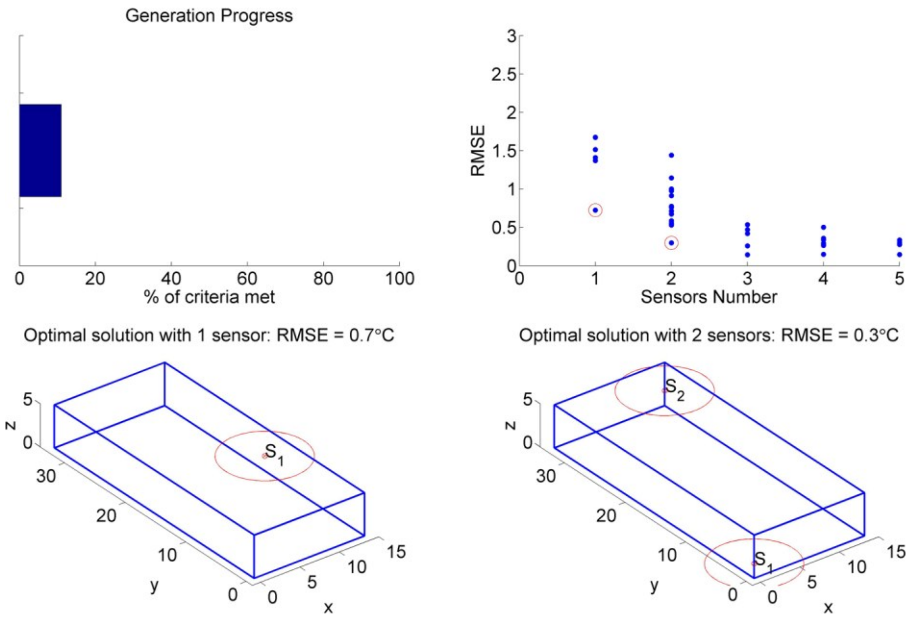

Figure 5 Output of the SOU with the two optimal solutions for the swimming pool positioned in the space

Then the complete application of the SOU is performed and the solution obtained, shown in Figure 5, is compared with the solution considering measured data. The initial validation shows a perfect correspondence between the solutions obtained, which confirms the validity of the proposed tool. The impact of this tool is assessed with the support of a simulation model and reported in Figure 6. The measurement accuracy is evaluated considering one month of measured data coming from the wireless sensors network installed in the swimming pool. The mean temperature value, evaluated as the mean of the six measurement points covered by the sensor network, constitutes the reference and then the uncertainty of three different sensor deployments is calculated:

1. The existent installation (one sensor installed and used by the HVAC control system) with an error equal to 0.9 °C;

2. The optimal solution with 1 sensor obtained with the SOU providing an error equal to 0.4 °C;

3. The optimal solution with 2 sensors obtained with the SOU providing an error equal to 0.3 °C.

The mentioned temperature deviations, which represent the systematic errors due to the sensors positioning, are used to estimate the impact on energy consumption. The air temperature value, used to control the heating system of the simulation model, is perturbed with the three deviations and the respective gas consumptions are taken. Then a baseline, which is the ideal condition with no uncertainty due to the sensors position, is created and used to compare the amount of energy used with the three conditions considering the deviation on the yearly gas consumption for space heating. The potential saving derived is equal to 4.3 % for the solution with one sensor and 5.2 % for the solution with two sensors.

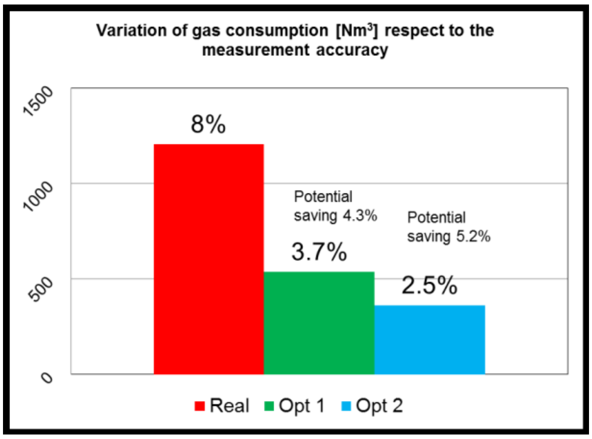

Figure 6 Impact of measurement accuracy on fuel consumption used for space heating

4 Conclusions

This dissertation defines a methodology to design and develop smart metering systems for sport facilities starting from state-of-art solutions and standards, mainly developed for generic commercial buildings. An innovative considered aspect is taking into account of comfort conditions in sport buildings and here the analysis of parameters to be measured and their practical evaluation to monitor thermal comfort are developed and presented. The ripened experience and exchange of views with the expertise allows to conclude that:

- A smart metering system has to provide a set of functionalities that makes tangible and visible how a building is operating. The presented design reaches this objective and places the approach a step beyond the state of the art with a dedicated comfort-based methodology;
- The proposed approach based on comfort evaluation opens new ways for control strategies, although a particular attention to measurement accuracy has to be used in order to achieve reasonable effects. Moreover, as discussed in the document, an adaptive approach could be considered to take into account the "thermal history" of the subject and then to evaluate the comfort feeling in a better way;

- Sport facilities are complex systems in terms of energy distribution/generation, building structure, air/water distribution and conditioning. Thus a scalable modular architecture is required. The presented solution allows a wide range of functionalities for the monitoring system that is fundamental to achieve this objectives;
- Considering Sport buildings, a lack for the optimization of the air temperature and humidity measurement in large spaces has been identified. Thus a dedicated tool is developed. This is particularly important to reach the right level of accuracy of the comfort measurement as revealed by the global sensitivity analysis. Moreover this will have a high impact on the control system as demonstrated with the simulation model.

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